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Three-Dimensional Hall Magnetic Reconnection

J.D. Huba
Plasma Physics Division
L.I. Rudakov
Berkeley Research Scholars, Inc.

Introduction: One of the most important and intriguing processes in space and laboratory plasmas is magnetic field line reconnection: it provides a mechanism to rapidly convert magnetic field energy into particle energy. For example, magnetic reconnection is considered to be a key factor in the onset and evolution of solar flares and magnetic storms. These two phenomena play a critical role in the dynamics of the near-Earth space environment, and are an integral part of "space weather" that can adversely impact communication and navigation systems.

The standard picture of magnetic reconnection is shown in Fig. 9, which depicts the evolution of a reconnecting, reversed field current layer, i.e., the magnetic field $\mathbf{B} = B_x \hat{e}_x$ reverses direction along $y = 0$. There is an inflow of plasma and magnetic field in the $\pm y$ direction with a velocity V_{in}, and an outflow in the $\pm x$ direction with a velocity V_{out}. The magnetic topology changes at the X-point where the red and blue field become interconnected. This region is often referred to as the "diffusion region" (the shaded box in Fig. 9). The release of magnetic tension associated with the strong curvature in the reconnected magnetic field lines leads to the acceleration of the plasma in the $\pm x$ direction. Typically, for fast reconnection $V_{in} \simeq 0.1\ V_A$ and $V_{out} \simeq V_A$, where V_A is the Alfvén velocity in the inflow region.

One of the major issues in reconnection physics is to understand the mechanism(s) for "fast reconnection" in collisionless plasmas. Conventional resistive

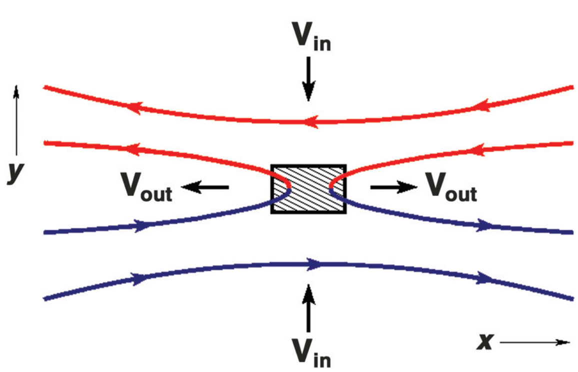

FIGURE 9
Standard, two-dimensional concept of magnetic field line reconnection.

magnetohydrodynamic (MHD) analysis leads to very slow reconnection rates in collisionless systems such as the solar corona and the Earth's magnetosphere. However, it has become evident that Hall physics can playa critical role in collisionless magnetic reconnection. The National Science Foundation Global Environment Modeling (GEM) challenge on reconnection physics concluded that Hall physics is the minimum physics needed to achieve fast reconnection—regardless of the mechanism that decouples the electrons from the magnetic field, i.e., allows the magnetic field lines to reconnect.[1] Physically, the Hall term decouples the ion and electron motion on length scales comparable to the ion inertial length. In essence, the electrons remain magnetized while the ions become unmagnetized. In recent years, NRL has carried out a number of studies to better understand the Hall dynamics of magnetic reconnection.

3D Simulation Results: We have carried out the first three-dimensional (3D) study of Hall magnetic reconnection[2] using the NRL Hall MHD code VooDoo.[3] Figure 10 illustrates the key findings. Figure 2(a) shows the initial configuration of the system. The color-coded slabs are in the x-y plane (same as Fig. 9) and denote the density:red indicates $n = 5n_0$ and blue indicates $n = n_0$, where n_0 is the density at the $\pm y$ boundary at $t = 0$. The white lines at $z = 0$ represent magnetic field lines. Lastly, the simulation is initiated with a magnetic perturbation localized in the z direction ($-20 > z > -30$). This perturbation is shown by the red and yellow isosurfaces of the magnetic field in the y direction and are indicative of magnetic reconnection.

Figure 10(b) shows the system at the end of the simulation run. A number of interesting features are observed. First, the magnetic perturbation induces a magneticwave structure that propagates in the direction of the electron drift (i.e., $-z$ direction). This wave is a Hall phenomenon associated with the curvature in the magnetic field (i.e., the curved field lines in the diffusion region shown in Fig. 9). Second, as this wave propagates, it leads to the thinning of the plasma current layer and the triggering of fast reconnection. In Fig. 10(b) magnetic reconnection is occurring in the region $20 > z > -20$, as evidenced by the elongated isosurfaces of B_y and is not isolated to a thin region in the z direction. Third, as reconnection proceeds, the magnetic field lines are "bent" in the $-z$ direction leading to the quadrupole magnetic field structure in B_z that has been observed in 2D simulation studies. This field line bending can be seen in the vicinity of the origin in Fig. 10(b) ($x = y = z = 0$). Finally, after

magnetic reconnection occurs, the release of magnetic tension also leads to plasma acceleration in the $+z$ direction, not just in the x direction as shown in Fig. 9. We find that $V_z \simeq 0.5\ V_A$.

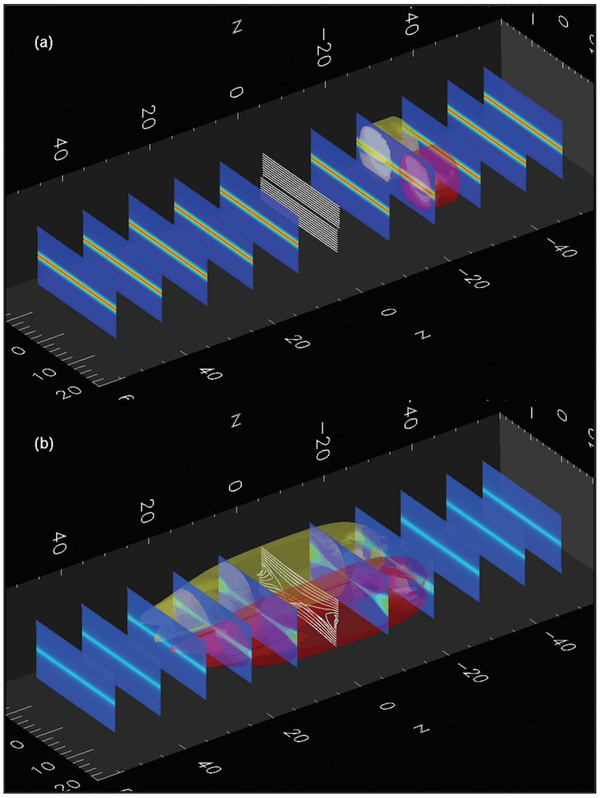

FIGURE 10
Three-dimensional simulation study of magnetic field line reconnection using the NRL Hall MHD code VooDoo.

Conclusion: A major new finding in this research is that a localized magnetic perturbation along the current in a reversed-field plasma system dominated by Hall physics initiates a shock-like "reconnection wave" that propagates asymmetrically along the current channel and leads to an extended region of reconnection. Laboratory experiments using the Space Chamber in the Plasma Physics Division are now being designed to test this result. In addition, these results are relevant to the dynamics of the Earth's magnetosphere; specifically, at the magnetopause and in the magnetotail where thin current layers exist and Hall magnetic reconnection processes can reconfigure the magnetic topology and energize the plasma.

[Sponsored by ONR and NASA]

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